Seismic Analysis and FRP Jacketing of 4-storey RC Building

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS OF THE DEGREE FOR THE DEGREE OF

Bachelor in Technology

in

Civil Engineering

By Manotapa Bhaumik

109CE0438

Under the guidance of

Prof AV Asha

Department of Civil Engineering

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Certificate

This is to certify that the project entitled —Seismic Analysis and FRP Jacketing of 4-storey RC Building submitted by **Ms. Manotapa Bhaumik** [Roll No. 109CE0438] in partial fulfillment of the requirements for the award of Bachelor of Technology degree in Civil Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge the matter embodied in the project has not been submitted to any other university/institute for the award of any degree or diploma.

Date: 10th May 2013

Prof A.V.Asha

Department of Civil Engineering

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Manotapa Bhaumik

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ABSTRACT

Keywords- Equivalent Static Method, Demand Capacity Ratio, Flexural Capacity, Shear Capacity, Reinforced Concrete Structure, FRP Strengthening

In the recent past, India has seen mass destruction due to failure of structures hit by earthquakes and consequently, lost a lot of lives. Hence, it is of utmost importance that attention be given to the evaluation of the adequacy of strength in framed RC structures to resist strong ground motions. In this project, a 50-year old four storey reinforced concrete structure has been considered, which lies in Zone II according to IS 1893:2000 classification of seismic zones in India. For non-structural members masonry infill has been assumed.

In the Equivalent Static Method of analysis, the seismic load acting on the structure is assumed to be an equivalent static horizontal force applied to individual frames. The total force applied shall be equal to the product of the acceleration response spectrum and the seismic weight. It is used only for low to high rise buildings without significant coupled lateral-torsional modes.

The structure is designed in STAAD.Pro v8i, considering M15 concrete and Fe250 steel reinforcement for with and without earthquake loading conditions. The demand moments and shear have been noted down from the software analysis and compared to the capacities of the given section.

FRP jacketing is the most appropriate method of retrofitting the failing members in the given 4-storey RC structure. The norms stated in ACI 440-2R.02 have been followed to calculate and suggest the method and scheme of application of FRPs to the member and also the number of plies to be used. Thereafter, an analysis has been done on the amount of efficiency achieved in dealing with the deficiency in the members. The FRP strengthening system has been checked for serviceability as well as creep-rupture limits since the entire modelling, analysis and design for the structure has been done using limit state design.

The limitations of this project are that not much is known about the behavior of FRP materials and thus, no standardization has been achieved in it commercially. Also the code does not give a specific method of jacketing columns.

Chapter 1

INTRODUCTION

1.1 General

Earthquakes around the world are single-handedly responsible for the destruction to life and property in large numbers. In order to mitigate such hazards, it is important to incorporate norms that will enhance the seismic performance of structures.

According to the Seismic Zoning Map of IS 1893:2002, India is divided into five seismic zones, in ascending order of a certain zone factor which is assigned to them on the basis of their seismic intensity. The 4-storey RC Structure being analysed in this particular project is the main institute building of NIT Rourkela, which is located in the least susceptible zone i.e. zone II. However, considering that the primary structural system of the building is at least 50 years old, it was not designed according to the design provisions given in IS 1893:2002. Hence, it may fail in the event of any moderately strong tectonic activity in its vicinity. Studying the performance of the structure and suggesting suitable retrofit measures for the building would therefore be a necessity.

Performance-based earthquake engineering deals with the seismic design of structures that will meet more than one performance level. The levels are- Operational, Immediate Occupancy, Life-Safety and Near Collapse and they are based on their hazard level as well as annual probability of exceedance.

Any Reinforced Concrete frame building has the following sources of weakness-

- Discontinuous load path/interrupted load path/irregular load path
- Lack of deformation capability of structural members
- Quality of workmanship and materials

Seismic retrofitting is the modification of existing structures to make them more resistant to seismic activity, ground motion, or soil failure due to earthquakes. This goal maybe achieved by adopting one of the following strategies-

- By reducing the seismic demands on members and the structures as a whole
- By increasing the member capacities

Stiffness, strength and ductility are the basic seismic response parameters taken into consideration while retrofitting. However, the choice of the technique to be applied depends on locally available materials and technologies, cost considerations, duration of the works and architectural, functional and aesthetic considerations/restrictions.

Retrofit strategies are different from retrofit techniques, where the former is the basic approach to achieve an overall retrofit performance objective, such as increasing strength, increasing deformability, reducing deformation demands while the latter is the technical methods to achieve that strategy.

Seismic retrofitting schemes can be either global or local, based on how many members of the structures they are used for. Global (Structural level) Retrofit methods include conventional methods (increase seismic resistance of existing structures) or non-conventional methods (reduction of seismic demand).

Some popular seismic retrofit techniques are-

i. RC Shear Wall
ii. Steel Bracings
iii. Infill Walls
iv. Wing Walls
v. Global Mass Reduction
vi. Seismic Base Isolation
vii. Supplemental Damping
viii. Thickening of members
ix. Jacketing

Jacketing is a member-level retrofit technique. It can be used to increase concrete confinement, shear or flexural strength of the members. Popular practices involve jacketing with concrete, steel or fiber reinforced polymers (FRP).

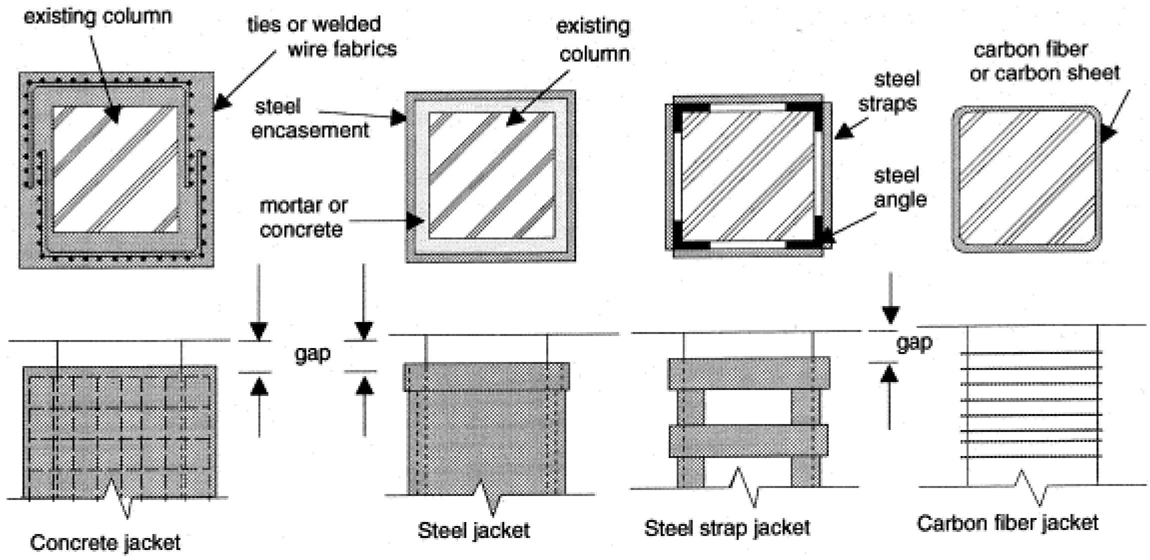


Fig. 1.1 Types of jacketing in seismic retrofitting

Despite their high cost-to-weight ratio, FRPs are increasingly becoming the preferred choice for jacketing because of-

- High strength-to-weight ratio
- Immunity to corrosion
- Easy handling and application
- Very small thickness
- Have almost no effect on the external aesthetics of the structure
- High tensile strength

The only drawback of FRPs is that they are sensitive to fire and temperature.

The fiber reinforced polymers used for strengthening civil engineering structures are made of carbon, glass or aramid.

i. Carbon fibers- Stable under high temperature. Resistant to acidic/alkali/organic environments. High stiffness and tensile strength. More expensive
ii. Glass fibers-E-glass (less expensive), AR-glass (alkali-resistant), S-glass (stronger and stiffer)
iii. Aramid fibers- Polymeric fibers appropriately processed to achieve high tensile strength-to-density ratio

The choice of the type of FRP to be used is based on the tensile behaviour, stiffness, compressive behaviour, endurance to creep-rupture and fatigue, and durability. Carbon fibers are the best choice when it comes to using FRPs. It is flexible and can be made to contact the surface tightly for a high degree of confinement. The tensile strength and modulus of elasticity for carbon fibers is higher than that for glass or aramid fibers. It has the least coefficient of thermal expansion amongst FRP materials and is resistant to alkaline or acidic environments. Another advantage is that carbon fibers are highly resistive to creep-rupture under sustained loading and fatigue failure under cyclic loading.

Fibers come in the form of flexible sheets which are impregnated in-situ in a matrix, typically a thermosetting polymer that also serves as an adhesive to the concrete structure. The matrix binds the fibers together, transfers the load onto the fibers and protests them from in-situ abrasion and adverse environmental effects. Epoxy resins, polyesters resins and vinyl esters are popularly used as matrix materials. Commercially available FRP systems can be of the types wet layup, prepreg or procured.

1.2 Proposed Work and Objective

My research project aims at doing seismic evaluation for the institute main building and suggesting how to retrofit the failing members, using FRP jacketing.

The institute main building is currently the most prominent building in the institute area. However, since it was constructed some 50 years earlier, it wasn't designed to withstand earthquakes. A thesis done earlier reveals that the structure will invariably fail when subjected to earthquake loads.

A thesis done earlier using Equivalent Static Method reveals that the structure will invariably fail when subjected to earthquake loads. The Demand Capacity Ratio (DCR) was calculated for beams and columns, only in the first storey. A large number of beams and columns were found to fail under flexural capacity. However, most of these members were found to pass in shear.

Taking the above results into consideration, my objective is to-

i. Analyse the seismic performance of the structure according to the design generated by STAAD.Pro v8i
ii. Calculate the Demand Capacity Ratio of the members of the remaining three storeys
iii. Calculate and suggest number of plies to be used for jacketing the failing members with FRP
iv. Check the efficiency of the failing members in sustaining the demand moment or maximum shear generated due to the earthquake forces, after retrofitting
v. Check whether the suggested level of jacketing satisfies all the required limits of design and is feasible or not.

1.3 Outline of the Work

Chapter 1 is a brief introduction about earthquakes, the necessity to analyse performance of structures when subjected to seismic forces and an overview about the various retrofitting techniques. It also summarizes the objective to be achieved in this particular project.

Chapter 2 contains a summary of all the literature which has been reviewed to gain knowledge about the various types of retrofitting measures which can be applied to structures and highlights the study area for the same.

Chapter 3 contains the main theory and methodology which has been used to analyse the structure and the design the FRP jacketing for the failing members. Essential concepts have been explained for the same and the formulae used have been stated.

Chapter 4 binds together all the results obtained from the analysis, which helps in pointing out which members will fail in flexure and/or shear and identify a pattern. The number of plies of FRP to be used to retrofit the failing members have been calculated. Consequently, certain conclusions have been derived and scope for future work has also been stated.

Chapter 2

LITERATURE REVIEW

2.1 Literature Review

Yen-Po Wang [11] introduced the fundamentals of seismic base isolation as an effective technique for seismic design of structures. Spring-like isolation bearings reduce earthquake forces by changing the fundamental time period of the structure to avoid resonance. However, sliding-type isolation bearings filter out the earthquake forces via discontinuous sliding interfaces and forces are prevented from getting transmitted to the superstructure because of the friction. The design of the base isolation system includes finding out the base shear, bearing displacement etc. in accordance with site-specific conditions.

M C Griffith And A V Pinto [4] have investigated the specific details of a 4-storey, 3-bay reinforced concrete frame test structure with unreinforced brick masonry (URM) infill walls are described along with estimates of its likely weaknesses with regard to seismic loading. The concrete frame is shown to be essentially a "weak-column strong-beam frame" which is likely to exhibit poor post yield hysteretic behavior. Based on the results of an extensive literature review, the building is expected to have maximum lateral deformation capacities corresponding to about 2% lateral drift. The unreinforced masonry infill walls are likely to begin cracking at much smaller lateral drifts, of the order of 0.3%, and to completely lose their load carrying ability by drifts of between 1% and 2%.

Hiroshi Fukuyama and Shunsuke Sugano [3] have emphasized on the importance of seismic rehabilitation, taking a leaf out of the destruction caused by the 1995 Kobe earthquake. Many new techniques like seismic isolation, supplemental damping and continuous fiber wrapping were implemented after the disaster out of which the fiber wrapping became the most popular method. Details about the technique, replete with diagrams, were discussed.

Jong-Wha Bai [12] studied the Seismic Retrofit for Reinforced Concrete Building Structures and proposed a relatively new paradigm, performance-based design, has also had an impact on seismic retrofitting and rehabilitation. This concept provides a new approach to design objectives and desired performance levels. As the performance-based design paradigm become more accepted for new structures, seismic retrofitting and rehabilitation methods have been affected by this concept. Consequently, retrofitting procedures could be selected and applied so that the performance objective of the retrofit depends upon the importance of the structure and the desired structural performance during a seismic event with a particular recurrence interval.

Luigi Di Sarno and Amr S. Elnashai [8] assessed the seismic performance of a 9-storey steel perimeter MRF (moment resisting frame) using the three types of bracings: special concentrically braces (SCBFs), buckling-restrained braces (BRBFs) and mega-braces (MBFs). Local (member rotations) and global (inter-storey and roof drifts) deformations were employed to compare the inelastic response of the retrofitted frames. MBFs were found to be the most cost-effective bracing system with the least storey drifts and hence, the most attractive system to be employed.

Giuseppe Oliveto and Massimo Marletta [6] considered the retrofitting of buildings vulnerable to earthquakes and briefly described the main traditional and innovative methods of seismic retrofitting. Among all the methods of seismic retrofitting, particular attention was devoted to the method which was based on stiffness reduction. This method was carried out in practice by application of the concept of springs in series, which lead in fact to base isolation. One of the two springs in series represented the structure and the other represented the base isolation system. The enhanced resistance of the buildings to the design earthquake clearly showed the effectiveness of the method, while a generally improved seismic performance also emerged from the application.

G E Thermou and A S Elnashai [10] made a global assessment of the effect of repair methods on stiffness, strength and ductility, the three most important seismic response parameters, to assist researchers and practitioners in decision-making to satisfy their respective intervention objectives. Also the term 'rehabilitation' was used as a comprehensive term to include all types of repair, retrofitting and strengthening that lead to reduced earthquake vulnerability. The term 'repair' was defined as reinstatement of the original characteristics of a damaged section or element and is confined to dealing with the as-built system. The term 'strengthening' was defined as intervention that lead to enhancement of one or more seismic response parameters (stiffness, strength, ductility, etc.), depending on the desired performance.

E. Senthil Kumar, A.Murugesan and G.S.Thirugnanam [5] did an experimental investigation of the behavior of retrofitted FRP (fiber reinforced polymer) wrapped exterior beam-column joint of a G+4 building in Salem, which lies in seismic zone III. The test specimen was taken to be one fifth model of beam column joint from the prototype specimen and was evaluated in terms of load displacement relation, ductility, stiffness, load ratio and cracking pattern. On comparing the test results with the analytical modeling of the joint on ANSYS and STAAD Pro, it was found that such external confinement of concrete increased the load carrying capacity of the control specimen by 60% and energy absorption capacity by 30-60%.

Durgesh C. Rai [7] gave the guidelines for seismic evaluation and strengthening of buildings. This document is developed as part of project entitled ―Review of Building Codes and Preparation of Commentary and Handbooks‖ awarded to Indian Institute of Technology Kanpur by the Gujarat State Disaster Management Authority (GSDMA), Gandhinagar through World Bank finances. This document is particularly concerned with the seismic evaluation and strengthening of existing buildings and it is intended to be used as a guide.

2.2 Summary of Review

A thorough study was done on literature regarding the latest developments in the field of seismic strengthening and rehabilitation. The necessity of implementing performance-based design in earthquake prone areas, was emphasized on. Studies revealed that stiffness, strength and ductility were the most important seismic response parameters to be kept in mind while selecting the method of retrofitting to be used. The fundamentals of base isolation, steel bracings and use of FRP were analysed. FRP jacketing was found to be the most suitable method for locally retrofitting a structure without defacing it or contributing to any significant gain in weight. The increase in efficiency of the structure was also noticed to be healthy when implemented on a prototype in India, similar to the 4-storey RC structure being considered in this project.

2.3 Study Area

Seismic Engineering is a sub discipline of the broader category of Structural engineering. Its main objectives are-

- To understand interaction of structures with the shaky ground.
- To foresee the consequences of possible earthquakes.
- To design, construct and maintain structures to perform at earthquake exposure up to the expectations and in compliance with building codes.

In the same realm, seismic analysis is a subset of structural analysis and is the calculation of the response of a structure to earthquakes. It is part of the process of structural design, earthquake engineering or structural assessment and retrofit in regions where earthquakes are prevalent. Structural analysis methods can be divided into the following categories-

- Equivalent Static Analysis
- Response Spectrum Analysis
- Linear Dynamic Analysis
- Nonlinear Static Analysis
- Nonlinear Dynamic Analysis

In the Equivalent Static Method, seismic load is assumed to be an equivalent static horizontal force applied to individual frames. The structure is assumed to be in its fundamental mode itself. For this to be true, the building must be low-rise and must not twist significantly when the ground moves. The response is read from a design response spectrum, given the natural frequency of the building (either calculated or defined by the building code). As per IS 1893 (Part 1): 2002, the total design lateral force or design seismic base shear is found to be the product of the design horizontal acceleration spectrum value and the seismic weight of the building. This force shall be applied to the vertical centre of mass of the superstructure and distributed horizontally in proportion to the mass distribution. Under this method of analysis, the Demand Capacity Ratio is calculated to find out which members are failing, either in flexural or shear capacity.

As per new retrofitting techniques developed, externally bonded FRP systems can be used for strengthening concrete systems to resist higher design loads, correct deterioration-related damage or increase ductility. An FRP system consists of fibers and resins used to create a composite laminate, resins to bond it to concrete and coatings applied to protect the constituent materials.

FRP systems are relatively expensive compared to the cost of traditional materials or equipment used. However, FRP materials are light weight, non-corrosive and have high tensile strength which makes them ideal to be used in seismic retrofitting techniques. The advantages of FRP hence help nullify the high initial investment required for the operation. As it is a relatively new genre of civil engineering materials used, the standard code which has been used for the design of FRP jacketing for the given structure is ACI 440.2R-02. Also future research has been suggested in the above code to determine certain material properties, behaviour of FRP-wrapped members under flexure/axial force and shear, and the detailing of such systems.

Chapter 3

THEORY AND FORMULATION

3.1 Theory

3.1.1. Demand Capacity Ratio

The calculation of Demand Capacity Ratio to identify the failing members, is the part of Equivalent Static Analysis.

Demand is the amount of force or deformation imposed on an element or component (in this case, with respect to earthquake loading). Capacity is the permissible strength or deformation of a structural member or system (from the existing frame of the building).

DCR= Demand/Capacity

If DCR is lesser than 1, the member passes, else it passes. It is an important tool used to determine whether a certain member of the structure is passing or failing due to moment and/or shear. The check for DCR exceeding 1 was performed for both flexural and shear capacities of the beams as well as columns of the structure.

To avoid failure, the following methods can be adopted-

- Reducing the loads acting on the member
- Increasing the area of the section
- Replacing with a material of higher strength

The third method has been used to deal with the failing members i.e. strengthening the failing members with FRP.

3.1.2. FRP Strengthening of Concrete Members

The design philosophy for such sections is coherence with limit state principles. This approach sets acceptable levels of safety against the occurrence of both serviceability limit states (excessive deflections, cracking) and ultimate-limit states (failure, stress rupture, fatigue).

While calculating the flexural resistance of a section strengthened with an externally applied FRP system, the following assumptions are made-

- Design calculation are based on the actual dimensions, internal reinforcing steel arrangement, material properties of the existing member being strengthened
- The strains in the reinforcement and concrete are directly proportional to the distance from the neutral axis, that is a plane section remains plane even after loading
- There is no relative slip between the concrete and the external FRP reinforcement
- The shear deformation within the adhesive layer is neglected since it is very thin with slight variation in thickness
- The maximum usable compressive strain in concrete is 0.003
- The tensile strength of concrete is neglected
- The FRP reinforcement has a linear elastic stress-strain relationship to failure

An additional strength reduction factor is used to compensate for the assumptions made.

According to the code ACI 440.2R-02, the following flexural failure modes are to be investigated in a FRP-strengthened section-

- Crushing of the concrete in compression before yielding of the reinforcing steel
- Yielding of the steel in tension followed by rupture of the FRP laminate
- Yielding of the steel in tension followed by concrete crushing
- Shear/tension delamination of the concrete cover (cover delamination)
- Debonding of the FRP from the concrete substrate

By applying limit state analysis, the internal strain and stress distribution for a rectangular section of concrete can be found out at the ultimate stage. Thereafter, the strain level in the FRP reinforcements can be determined. Since FRP materials are linearly elastic until failure, the stress in the FRP reinforcement will be dictated by the strain developed. The maximum strain for the FRP will be developed at the point at which concrete crushes, FRP ruptures or FRP debonds from the substrate.

After determining the depth of the neutral axis by trial and error method, the nominal flexural strength of the section with FRP external reinforcement can be computed and the stress in the existing steel can be determined, under service loads, based on cracked elastic analysis. Consequently, the stress in FRP under service loads can be determined.

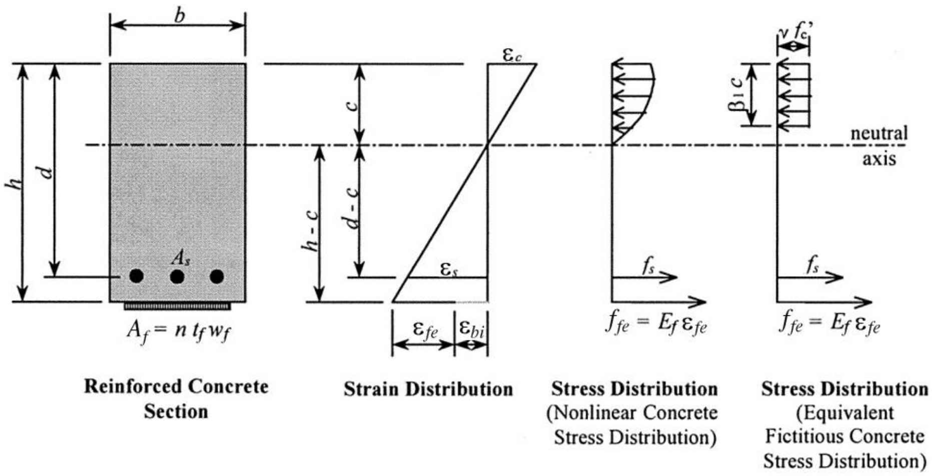


Fig 3.1 Internal strain and stress distribution for a rectangular concrete section (FRP strengthened) under flexure at ultimate stage

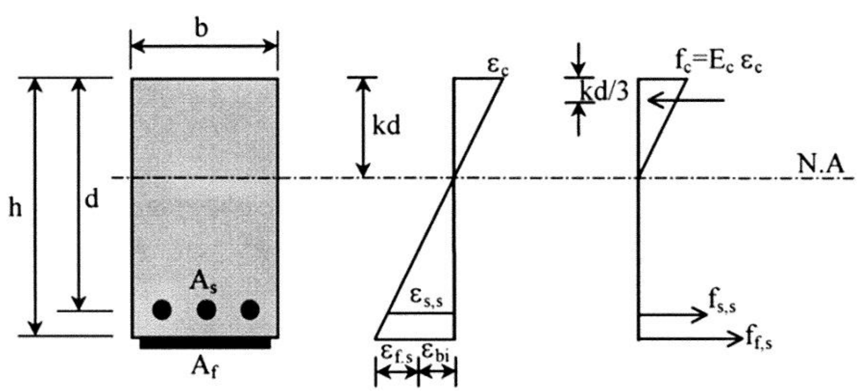


Fig. 3.2 Elastic strain and stress distribution

ACI- 440.2R-02 (Clause 11.3.2) mentions that confining rectangular sections with FRP is effective in improving the ductility of compression members but not in increasing their axial strength. Hence, due to lack of any suggested method, the design of FRP jacketing was performed only for the failing beams.

3.2. Methodology

3.2.1 Calculation of DCR

The method of analysis used in the project is Equivalent Static Method. The initial part of analysis to determine the members that fail under earthquake loading is done by calculating the Demand-Capacity Ratio (DCR) for each member individually. Determining which members will fail is essential because it gives a rough idea about which retrofit technique to proceed with- global or local.

The detailed evaluation of the building involves equivalent static lateral force procedure, load with response reduction factors and Demand Capacity Ratio (DCR) for ductility as in IS 13920:1993. Since the building dates back to a period 50 years early, the grade of concrete is assumed to be M15 and for steel Fe250.

Checks done:

1. DCR for moments of resistance in sagging and hogging for beams
2. DCR for shear capacity in beams
3. DCR for moment of resistance in columns
4. DCR for shear capacity in columns

- **Steps for finding DCR for moments of resistance in sagging and hogging:**

i. Obtain the maximum moment for the beam from design with earthquake loading. This is the demand moment.

ii. For finding depth of neutral axis Xu (from design without earthquake loading)

$0.36f_{ck}bX_u + f_{sc}A_{sc} = 0.87f_yA_{st}$

where $f_{sc} = 700\ (1- (d'/X_u))$

iii. In hogging, the capacity moment of resistance is found out by the formula-

$Mr\ (H) = 0.36f_{ck}bX_u\ (d- 0.44X_u) + f_{sc}A_{sc}\ (d-d')$

In sagging, the capacity moment of resistance is found out by the formula-

$Mr\ (S) = 0.36f_{ck}bX_u\ (d- 0.44X_u) + f_{sc}A_{st}\ (d-d')$

d' = effective cover= 33 mm

iv. DCR is calculated separately for both sagging and hogging.
    DCR = Demand/ Capacity
v. If DCR <1, the member is labelled PASS i.e. it can take the moment induced by the seismic loading.
vi. If DCR >1, the member is labelled FAIL i.e. it cannot take the moment induced by the seismic loading.

- **Steps for finding DCR for moments of resistance in columns:**

i. Obtain the maximum moment for the column from design with earthquake loading. This is the demand moment.
ii. The percentage of steel for the given section is calculated-
    $P_s = (A_s/bD)*100$
iii. The Interaction diagram in SP-16 has been used to find the value of $M_u/f_{ck}bD^2$ for the corresponding values of p/f_{ck} and $P_u/f_{ck}bD$
iv. Value of capacity moment is found out from the above i.e. M_u
v. DCR = Demand/ Capacity
vi. If DCR <1, the member is labelled PASS i.e. it can take the moment induced by the seismic loading.
vii. If DCR >1, the member is labelled FAIL i.e. it cannot take the moment induced by the seismic loading.

- **Steps for finding DCR for shear capacity of beams:**

i. Obtain the maximum shear for the beam from design with earthquake loading. This is the maximum shear to be resisted (demand).
ii. Note down the spacing S_v of the 2-legged stirrups from the concrete design for the beam, without seismic loading.
iii. Calculate the percentage of steel $100A_s/bd$.

iv. For the corresponding percentage, find the value of τc(design shear strength of concrete) from table 19 of IS 456: 2000. The following are calculated-

$V_{us} = 0.87\ f_y A_{sv}\ d / S_v$

$V_{u1} = V_{us} + \tau_c bd$

$V_{u2} = 1.4\ [M_R(H) + M_R(S)] / L_c$

whereL_c= clear span of the member

v. Shear resisted (capacity) is given by the maximum of V_{u1} and V_{u2}.

vi. If DCR <1 , the member is labelled PASS i.e. it can take the shear induced by the seismic loading.

vii. If DCR >1, the member is labelled FAIL i.e. it cannot take the shear induced by the seismic loading

- **Steps for finding DCR for shear capacity of columns:**

i. Obtain the maximum shear for the column from design with earthquake loading. This is the maximum shear to be resisted (demand).

ii. Note down the spacing S_v of the 2-legged stirrups from the concrete design for the column, without seismic loading.

iii. Calculate the percentage of steel $100A_s/bd$.

iv. For the corresponding percentage, find the value of τc(design shear strength of concrete) from table 19 of IS 456: 2000. The following are calculated-

$V_{us} = 0.87\ f_y A_{sv}\ d / S_v$

$V_{u1} = V_{us} + \tau_c bd$

$V_{u2} = 1.4\ [M_R(L) + M_R(R)] / H_c$

Where H_c= height of the member

v. Shear resisted (capacity) is given by the maximum of V_{u1} and V_{u2}.

vi. If DCR <1 , the member is labelled PASS i.e. it can take the shear induced by the seismic loading.

vii. If DCR >1, the member is labelled FAIL i.e. it cannot take the shear induced by the seismic loading.

3.2.2 Design of FRP Jacketing

- **Steps for providing flexural strengthening to beams using FRP:**

i. Calculate the FRP system design properties-$f_{fu}= C_E\, f_{fu}*$

$\varepsilon_{fu}= C_E\, \varepsilon_{fu}*$

where $f_{fu}*$= ultimate tensile strength of FRP

$\varepsilon_{fu}*$=rupture strain of FRP

C_E= environmental reduction factor

ii. Find percentage of existing reinforcing steel $p_s=A_s/bd$ and externally bonded FRP

$p_f= A_f/bd$

where $A_f= nt_f w_f$

iii. Determine the existing strain in the soffit-

$\varepsilon_{bi}= M_{DL}(h - kd)/ I_{cr}E_c$

iv. Determine the bond-dependent coefficient and check limits-

$k_m =(1- (nt_f w_f/2000000))/60\varepsilon_{fu}<= 0.6$

v. A depth of neutral axis c is assumed.

vi. Determine the effective level of strain in the FRP reinforcement level and check limits-

$\varepsilon_{fe}= 0.03(h-c)/c - \varepsilon_{bi}<= k_m\varepsilon_{fu}$

vii. Calculate the strain in the existing steel-

$\varepsilon_s= (\varepsilon_{fe}+\varepsilon_{bi})\ (d-c)/(h-c)$

viii. Calculate the stress level in the reinforcing steel and FRP-

$f_s= E_s\varepsilon_s<= f_y$

$f_{fe}= E_f\varepsilon_{fe}$

ix. Calculate the internal force resultants and check equilibrium-

$c= (A_s f_s+A_f f_{fe})/\ g\ fc'\ \beta_1\ b$

The c obtained thus is compared with the one assumed in step v. If it does not match, another value of c is assumed and steps vi through ix are repeated.

x. Calculate the design flexural strength of the section-

$$\Phi M_n = \Phi[A_s f_s (d- b_1 c/2) + y A_f f_{fe}(h-b_1 c/2))]$$

This should be greater than the required moment strength M_u

xi. Calculate the service stresses in the reinforcing steel and the FRP by-

$$k= [(psEs/Ec + pfEf/Ec)^2 + 2 (psEs/Ec + pfEfh/Ecd)-(psEs/Ec + pfEf/Ec)]^{0.5}$$

$$f_{s,s} = \frac{[M_s + \varepsilon_{bi} A_f E_f (h- kd/3)](d - kd) E_s}{A_s E_s (d-kd/3) (d-kd) + A_f E_f (h - kd/3) (h-kd)}$$

$f_{s,s} <= 0.80\ f_y$ (Serviceability conditions)

$$f_{f,s} = f_{s,s}\ [E_f(h-kd)/E_s(d-kd)] - \varepsilon_{bi} E_f$$

$f_{f,s} <= 0.55\ f_u$ (Creep-rupture stress limit)

For the above calculations, values assumed are as follows-

Environmental Reduction Factor Ce for carbon fibers = 0.95

Rupture Strain of FRP system e_{fu}* = 0.017

Ultimate Tensile strength of FRP system f_{fu} * = 0.62kN/mm^2

Modulus of Elasticity of FRP system E_f = 37kN/mm^2

Dimensions of FRP strips

Thickness t_f = 0.04” = 1.016 mm

Width w_f = 12 in = 304.8 mm

Chapter 4

RESULTS AND CONCLUSIONS

4.1 Results

4.1.1 DCR Calculation for Beams

Moment Capacity of Beams

Table 4.1.1 1st Storey

Beam No.	Demand (kNm)	Capacity Sagging (kNm)	DCR Sagging	Result Sagging	Capacity Hogging (kNm)	DCR Hogging	Result Hogging
1	44.184	34.011	1.299109112	FAIL	34.011	1.2991091	FAIL
2	42.166	34.012	1.239738916	FAIL	34.012	1.2397389	FAIL
3	42.105	34.012	1.237945431	FAIL	34.012	1.2379454	FAIL
4	41.664	34.012	1.224979419	FAIL	34.012	1.2249794	FAIL
5	41.785	34.012	1.228536987	FAIL	34.012	1.228537	FAIL
6	42.158	34.012	1.239503705	FAIL	34.012	1.2395037	FAIL
7	41.522	34.012	1.220804422	FAIL	34.012	1.2208044	FAIL
8	44.431	34.01	1.306409879	FAIL	34.01	1.3064099	FAIL
11	44.328	35.622	1.244399528	FAIL	58.201	0.7616364	PASS
13	101.59	58.086	1.748958441	FAIL	125.645	0.8085479	PASS
14	102.405	50.328	2.034752027	FAIL	123.639	0.8282581	PASS
15	99.518	50.329	1.977349043	FAIL	112.7	0.8830346	PASS
16	92.931	40.971	2.268214103	FAIL	108.49	0.8565859	PASS
17	92.767	40.971	2.264211271	FAIL	108.49	0.8550742	PASS
18	98.034	50.328	1.947901764	FAIL	123.639	0.7929052	PASS
19	100.109	50.329	1.989091776	FAIL	110.541	0.9056278	PASS
20	92.615	44.856	2.064718209	FAIL	93.613	0.9893391	PASS
23	400.526	243.567	1.644418168	FAIL	460.281	0.8701771	PASS
24	109.261	75.889	1.439747526	FAIL	141.761	0.7707409	PASS
25	112.292	72.906	1.540229885	FAIL	127.291	0.8821676	PASS
26	106.209	69.672	1.524414399	FAIL	125.197	0.848335	PASS
27	97.311	51.021	1.907273476	FAIL	110.859	0.8777907	PASS
28	97.158	55.001	1.766476973	FAIL	111.248	0.873346	PASS
29	105.714	69.673	1.517287902	FAIL	126.993	0.8324396	PASS
30	107.219	69.673	1.538888809	FAIL	126.993	0.8442906	PASS
31	97.257	57.234	1.699287137	FAIL	122.974	0.7908745	PASS
35	306.418	301.599	1.01597817	FAIL	373.599	0.8201789	PASS
36	448.541	556.128	0.806542738	PASS	560.128	0.800783	PASS
37	294.079	190.597	1.542936143	FAIL	366.239	0.8029702	PASS
38	291.341	190.597	1.528570754	FAIL	366.239	0.7954942	PASS
39	292.528	190.597	1.534798554	FAIL	366.239	0.7987353	PASS
40	446.49	521.15	0.856739902	PASS	521.15	0.8567399	PASS

41	294.893	120.597	2.445276416	FAIL	366.239	0.8051928	PASS
42	220.503	105.454	2.09098754	FAIL	257.832	0.8552197	PASS
386	42.932	34.653	1.238911494	FAIL	56.46	0.7603967	PASS

Table 4.1.2 2nd Storey

Beam No.	Demand (kNm)	Capacity Sagging (kNm)	DCR Sagging	Result Sagging	Capacity Hogging (kNm)	DCR Hogging	Result Hogging
77	41.635	33.966	1.225784608	FAIL	33.966	1.225784608	FAIL
78	39.868	33.966	1.173761997	FAIL	33.966	1.173761997	FAIL
79	39.349	33.966	1.158482011	FAIL	33.966	1.158482011	FAIL
80	38.981	33.966	1.147647648	FAIL	33.966	1.147647648	FAIL
81	38.954	33.966	1.146852735	FAIL	33.966	1.146852735	FAIL
82	39.358	33.966	1.158746982	FAIL	33.966	1.158746982	FAIL
83	39.193	33.966	1.153889183	FAIL	33.966	1.153889183	FAIL
84	41.485	33.966	1.221368427	FAIL	33.966	1.221368427	FAIL
87	39.57	16.443	2.406495165	FAIL	16.297	2.428054243	FAIL
89	94.49	69.548	1.358630011	FAIL	48.516	1.947604914	FAIL
90	97.854	69.548	1.406999482	FAIL	48.516	2.016942864	FAIL
91	94.792	69.548	1.362972336	FAIL	48.516	1.953829664	FAIL
92	87.456	69.548	1.257491229	FAIL	48.516	1.802621815	FAIL
93	87.048	69.548	1.251624777	FAIL	48.516	1.794212219	FAIL
94	93.008	69.548	1.337320987	FAIL	48.516	1.91705829	FAIL
95	95.088	69.548	1.367228389	FAIL	48.516	1.959930744	FAIL
96	86.691	69.548	1.246491632	FAIL	48.516	1.786853821	FAIL
99	394.924	970.763	0.406818142	PASS	409.104	0.965338887	PASS
100	99.675	40.446	2.464396974	FAIL	40.446	2.464396974	FAIL
101	106.372	40.446	2.62997577	FAIL	40.446	2.62997577	FAIL
102	100.11	40.446	2.475152055	FAIL	40.446	2.475152055	FAIL
103	90.447	40.446	2.236240914	FAIL	40.446	2.236240914	FAIL
104	90.01	40.446	2.225436384	FAIL	40.446	2.225436384	FAIL
105	99.33	40.446	2.455867082	FAIL	40.446	2.455867082	FAIL
106	100.827	40.446	2.492879395	FAIL	40.446	2.492879395	FAIL
107	89.468	40.446	2.212035801	FAIL	40.446	2.212035801	FAIL
111	302.934	480.549	0.63039149	PASS	313.796	0.965385155	PASS
112	440.714	137.43	3.206825293	FAIL	136.211	3.235524297	FAIL
113	290.215	136.436	2.127114545	FAIL	135.57	2.14070222	FAIL
114	287.427	129.37	2.221743836	FAIL	128.566	2.235637727	FAIL
115	288.638	129.37	2.231104584	FAIL	128.566	2.245057014	FAIL

116	438.591	137.43	3.191377429	FAIL	136.211	3.219938184	FAIL
117	289.386	129.37	2.23688645	FAIL	128.566	2.250875037	FAIL
118	354.727	107.096	3.312233884	FAIL	106.659	3.325804667	FAIL
385	44.394	37.192	1.193643794	FAIL	37.192	1.193643794	FAIL

Table 4.1.3 3rd Storey

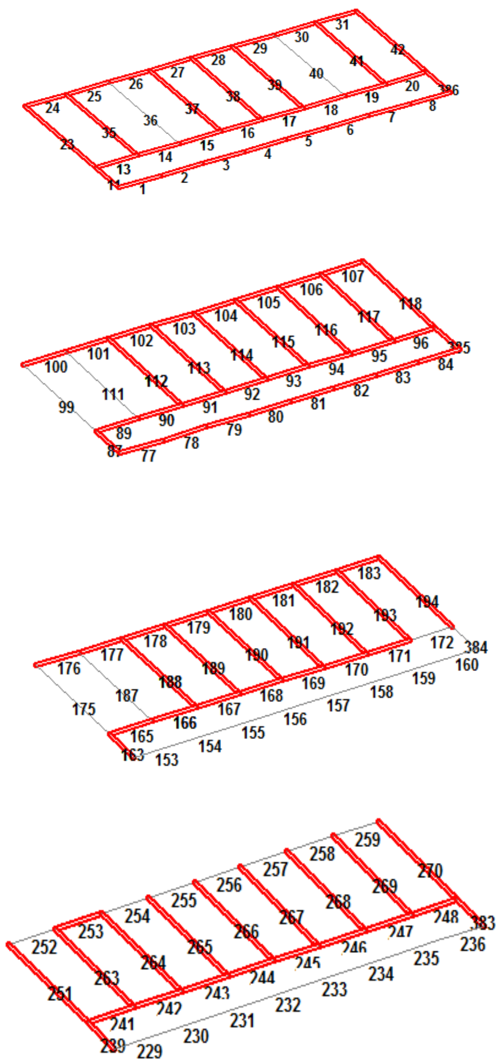
Beam No.	Demand (kNm)	Capacity Sagging (kNm)	DCR Sagging	Result Sagging	Capacity Hogging (kNm)	DCR Hogging	Result Hogging
153	32.794	33.966	0.965494907	PASS	33.966	0.965494907	PASS
154	32.611	33.966	0.960107166	PASS	33.966	0.960107166	PASS
155	32.97	33.966	0.970676559	PASS	33.966	0.970676559	PASS
156	32.597	33.966	0.959694989	PASS	33.966	0.959694989	PASS
157	32.457	33.966	0.95557322	PASS	33.966	0.95557322	PASS
158	32.859	33.966	0.967408585	PASS	33.966	0.967408585	PASS
159	33.18	33.966	0.976859212	PASS	33.966	0.976859212	PASS
160	32.423	33.966	0.954572219	PASS	33.966	0.954572219	PASS
163	32.127	16.443	1.95384054	FAIL	16.297	1.971344419	FAIL
165	74.554	69.548	1.071979065	FAIL	48.516	1.536688927	FAIL
166	80.358	69.548	1.155432219	FAIL	48.516	1.656319565	FAIL
167	77.532	69.548	1.114798413	FAIL	48.516	1.59807074	FAIL
168	70.557	69.548	1.014507966	FAIL	48.516	1.454303735	FAIL
169	69.716	69.548	1.002415598	FAIL	48.516	1.436969247	FAIL
170	75.755	69.548	1.089247714	FAIL	48.516	1.561443647	FAIL
171	77.483	69.548	1.114093863	FAIL	48.516	1.597060763	FAIL
172	69.493	69.548	0.999209179	PASS	48.516	1.432372825	FAIL
175	362.301	970.763	0.373212617	PASS	409.104	0.885596328	PASS
176	76.084	40.446	1.881125451	FAIL	40.446	1.881125451	FAIL
177	85.568	40.446	2.115610938	FAIL	40.446	2.115610938	FAIL
178	80.124	40.446	1.981011719	FAIL	40.446	1.981011719	FAIL
179	71.249	40.446	1.761583346	FAIL	40.446	1.761583346	FAIL
180	70.217	40.446	1.736067844	FAIL	40.446	1.736067844	FAIL
181	79.147	40.446	1.956856055	FAIL	40.446	1.956856055	FAIL
182	80.246	40.446	1.984028087	FAIL	40.446	1.984028087	FAIL
183	68.936	40.446	1.704395985	FAIL	40.446	1.704395985	FAIL
187	275.402	480.549	0.573098685	PASS	313.796	0.877646624	PASS
188	429.371	137.43	3.124288729	FAIL	136.211	3.152249084	FAIL
189	264.009	136.436	1.935039139	FAIL	135.57	1.947399867	FAIL
190	262.013	129.37	2.025299528	FAIL	128.566	2.037964936	FAIL
191	262.65	129.37	2.03022339	FAIL	128.566	2.04291959	FAIL

192	428.915	137.43	3.120970676	FAIL	136.211	3.148901337	FAIL
193	265.966	129.37	2.055855299	FAIL	128.566	2.06871179	FAIL
194	190.509	107.096	1.778861956	FAIL	106.659	1.786150255	FAIL
384	36.516	37.192	0.981824048	PASS	37.192	0.981824048	PASS

Table 4.1.4 Terrace

Beam No.	Demand (kNm)	Capacity Sagging (kNm)	DCR Sagging	Result Sagging	Capacity Hogging (kNm)	DCR Hogging	Result Hogging
229	17.826	33.966	0.524818937	PASS	33.966	0.524818937	PASS
230	22.182	33.966	0.65306483	PASS	33.966	0.65306483	PASS
231	21.264	33.966	0.626037803	PASS	33.966	0.626037803	PASS
232	20.986	33.966	0.617853147	PASS	33.966	0.617853147	PASS
233	20.92	33.966	0.615910028	PASS	33.966	0.615910028	PASS
234	21.106	33.966	0.621386092	PASS	33.966	0.621386092	PASS
235	21.8	33.966	0.641818289	PASS	33.966	0.641818289	PASS
236	17.114	33.966	0.503856798	PASS	33.966	0.503856798	PASS
239	26.452	16.443	1.608708873	FAIL	16.297	1.62312082	FAIL
241	32.311	20.766	1.555956853	FAIL	20.766	1.555956853	FAIL
242	37.358	20.766	1.798998363	FAIL	20.766	1.798998363	FAIL
243	34.641	20.766	1.668159491	FAIL	20.766	1.668159491	FAIL
244	29.257	20.766	1.408889531	FAIL	20.766	1.408889531	FAIL
245	29.388	20.766	1.41519792	FAIL	20.766	1.41519792	FAIL
246	33.476	20.766	1.612058172	FAIL	20.766	1.612058172	FAIL
247	35.213	20.766	1.695704517	FAIL	20.766	1.695704517	FAIL
248	28.521	20.766	1.373446981	FAIL	20.766	1.373446981	FAIL
251	181.786	124.965	1.454695315	FAIL	124.361	1.46176052	FAIL
252	34.818	40.446	0.860851506	PASS	40.446	0.860851506	PASS
253	42.967	40.446	1.06233002	FAIL	40.446	1.06233002	FAIL
254	38.097	40.446	0.941922563	PASS	40.446	0.941922563	PASS
255	31.638	40.446	0.782228156	PASS	40.446	0.782228156	PASS
256	31.923	40.446	0.789274588	PASS	40.446	0.789274588	PASS
257	37.402	40.446	0.924739158	PASS	40.446	0.924739158	PASS
258	39.093	40.446	0.96654799	PASS	40.446	0.96654799	PASS
259	30.256	40.446	0.748059141	PASS	40.446	0.748059141	PASS
263	177.643	129.279	1.374105617	FAIL	128.6	1.381360809	FAIL
264	182.458	106.074	1.720101062	FAIL	105.328	1.732283913	FAIL
265	170.208	140.375	1.212523598	FAIL	139.656	1.218766111	FAIL
266	168.496	140.375	1.200327694	FAIL	139.656	1.206507418	FAIL

267	170.079	140.375	1.21160463	FAIL	139.656	1.217842413	FAIL
268	180.97	106.074	1.706073119	FAIL	105.328	1.718156616	FAIL
269	169.737	140.375	1.209168299	FAIL	139.656	1.215393538	FAIL
270	160.556	110.854	1.448355495	FAIL	110.356	1.454891442	FAIL
383	31.084	11.589	2.682198637	FAIL	11.581	2.684051464	FAIL



First Storey

Second Storey

Third Storey

Terrace

Fig. 4.1 Beams Failing due to Flexural Capacity

Shear Capacity of Beams

Table 4.2.1 1st Storey

Beam No.	Max Shear (kN)	Shear Resisted (kN)	DCR	Result
1	57.278	131.97	0.434022884	PASS
2	52.439	131.97	0.39735546	PASS
3	52.464	131.97	0.397544897	PASS
4	52.069	131.97	0.394551792	PASS
5	52.035	131.97	0.394294158	PASS
6	52.506	131.97	0.397863151	PASS
7	51.974	131.97	0.393831931	PASS
8	56.553	131.97	0.428529211	PASS
11	34.446	119.133	0.289139029	PASS
13	102.93	131.97	0.779949989	PASS
14	113.103	131.97	0.85703569	PASS
15	111.837	131.97	0.847442601	PASS
16	106.236	131.97	0.805001137	PASS
17	106.308	131.97	0.805546715	PASS
18	110.865	131.97	0.84007729	PASS
19	112.105	131.97	0.849473365	PASS
20	107.247	131.97	0.812661969	PASS
23	231.938	220.076	1.053899562	FAIL
24	113.554	152.455	0.744836181	PASS
25	113.181	152.455	0.742389558	PASS
26	110.244	152.455	0.723124857	PASS
27	102.256	152.455	0.670729068	PASS
28	102.539	152.455	0.672585353	PASS
29	109.94	152.455	0.721130825	PASS
30	110.66	152.455	0.725853531	PASS
31	104.293	152.455	0.684090387	PASS
35	171.364	293.98	0.582910402	PASS
36	296.167	285.796	1.036288122	FAIL
37	170.205	293.98	0.578967957	PASS
38	168.774	293.98	0.574100279	PASS
39	169.559	293.98	0.576770529	PASS
40	295.45	253.308	1.166366637	FAIL
41	169.327	293.98	0.575981359	PASS
42	104.764	198.252	0.528438553	PASS
386	34.178	75.522	0.452556871	PASS

Table 4.2.2 2nd Storey

Beam No.	Maximum Shear (kN)	Shear Resisted (kN)	DCR	Result
77	53.15	53.15	8.50724365	PASS
78	51.57	51.57	8.767888307	PASS
79	50.969	50.969	8.871274696	PASS
80	50.642	50.642	8.928557324	PASS
81	50.504	50.504	8.952954221	PASS
82	51.033	51.033	8.860149315	PASS
83	51.074	51.074	8.85303677	PASS
84	52.378	52.378	8.632632021	PASS
87	30.349	30.349	7.449339352	PASS
89	109.243	109.243	3.592907555	PASS
90	110.005	110.005	3.568019635	PASS
91	108.609	108.609	3.613880986	PASS
92	102.573	102.573	3.826543047	PASS
93	102.416	102.416	3.832408999	PASS
94	107.406	107.406	3.65435823	PASS
95	108.612	108.612	3.613781166	PASS
96	103.131	103.131	3.805839175	PASS
99	231.911	231.911	4.231149018	PASS
100	106.664	106.664	5.151691292	PASS
101	109.105	109.105	5.036432794	PASS
102	106.042	106.042	5.181909055	PASS
103	97.652	97.652	5.627124892	PASS
104	97.624	97.624	5.628738835	PASS
105	105.507	105.507	5.208185239	PASS
106	106.144	106.144	5.176929454	PASS
107	98.937	98.937	5.554039439	PASS
111	157.938	157.938	9.940609606	PASS
112	296.119	296.119	4.750522594	FAIL
113	170.183	170.183	3.690145314	PASS
114	168.795	168.795	3.720489351	PASS
115	169.552	169.552	3.703878456	PASS
116	256.629	256.629	5.481531705	FAIL
117	169.147	169.147	3.712746901	PASS
118	230.11	230.11	0.982486637	FAIL
385	33.344	33.344	6.780230326	PASS

Table 4.2.3 3rd Storey

Beam No.	Maximum Shear (kN)	Shear Resisted (kN)	DCR	Result
153	48.561	48.561	9.311175635	PASS
154	51.073	51.073	8.853210111	PASS
155	50.061	50.061	9.032180739	PASS
156	49.421	49.421	9.149147124	PASS
157	49.069	49.069	9.214779188	PASS
158	50.072	50.072	9.030196517	PASS
159	50.334	50.334	8.983192276	PASS
160	47.29	47.29	9.561429478	PASS
163	24.88	24.88	9.08681672	PASS
165	95.266	95.266	4.120042827	PASS
166	98.287	98.287	3.993407063	PASS
167	96.887	96.887	4.051111088	PASS
168	91.341	91.341	4.297084551	PASS
169	90.744	90.744	4.325354844	PASS
170	95.686	95.686	4.101958489	PASS
171	96.609	96.609	4.062768479	PASS
172	91.921	91.921	4.269970953	PASS
175	232.136	232.136	4.227047937	PASS
176	90.344	90.344	6.082307624	PASS
177	95.091	95.091	5.778675164	PASS
178	92.349	92.349	5.950253928	PASS
179	84.903	84.903	6.472091681	PASS
180	84.265	84.265	6.521094167	PASS
181	91.671	91.671	5.994262089	PASS
182	92.011	92.011	5.97211203	PASS
183	85.495	85.495	6.427276449	PASS
187	171.341	171.341	9.163014106	PASS
188	295.941	295.941	4.753379897	FAIL
189	170.148	170.148	3.690904389	PASS
190	168.927	168.927	3.717582151	PASS
191	169.573	169.573	3.703419766	PASS
192	295.571	295.571	4.759330246	FAIL
193	169.424	169.424	3.70667674	PASS
194	105.565	105.565	2.141618908	PASS
384	30.348	30.348	7.449584816	PASS

Table 4.2.4 Terrace

Beam No.	Maximum Shear (kN)	Shear Resisted (kN)	DCR	Result
229	36.349	36.349	12.43940686	PASS
230	37.414	37.414	12.08531566	PASS
231	36.406	36.406	12.41993078	PASS
232	35.968	35.968	12.57117438	PASS
233	35.725	35.725	12.656683	PASS
234	36.479	36.479	12.39507662	PASS
235	36.982	36.982	12.22648856	PASS
236	35.584	35.584	12.70683453	PASS
239	30.462	30.462	7.421705732	PASS
241	38.499	38.499	10.19507	PASS
242	41.603	41.603	9.434415787	PASS
243	40.21	40.21	9.76125342	PASS
244	35.537	35.537	11.04482652	PASS
245	35.652	35.652	11.00920004	PASS
246	39.336	39.336	9.978137075	PASS
247	40.173	40.173	9.770243696	PASS
248	35.501	35.501	11.05602659	PASS
251	118.319	118.319	1.326921289	PASS
252	41.524	41.524	13.23331086	PASS
253	46.056	46.056	11.93112732	PASS
254	43.73	43.73	12.56574434	PASS
255	37.674	37.674	14.58565589	PASS
256	37.896	37.896	14.5002111	PASS
257	43.134	43.134	12.73937033	PASS
258	43.687	43.687	12.57811248	PASS
259	30.912	30.912	17.77626812	PASS
263	128.945	128.945	1.753305673	PASS
264	129.056	129.056	3.114306968	PASS
265	128.192	128.192	1.224725412	PASS
266	127.467	127.467	1.23169134	PASS
267	127.979	127.979	1.226763766	PASS
268	128.581	128.581	3.125811745	PASS
269	127.817	127.817	1.228318612	PASS
270	118.121	118.121	1.329145537	PASS
383	32.8	32.8	6.892682927	PASS

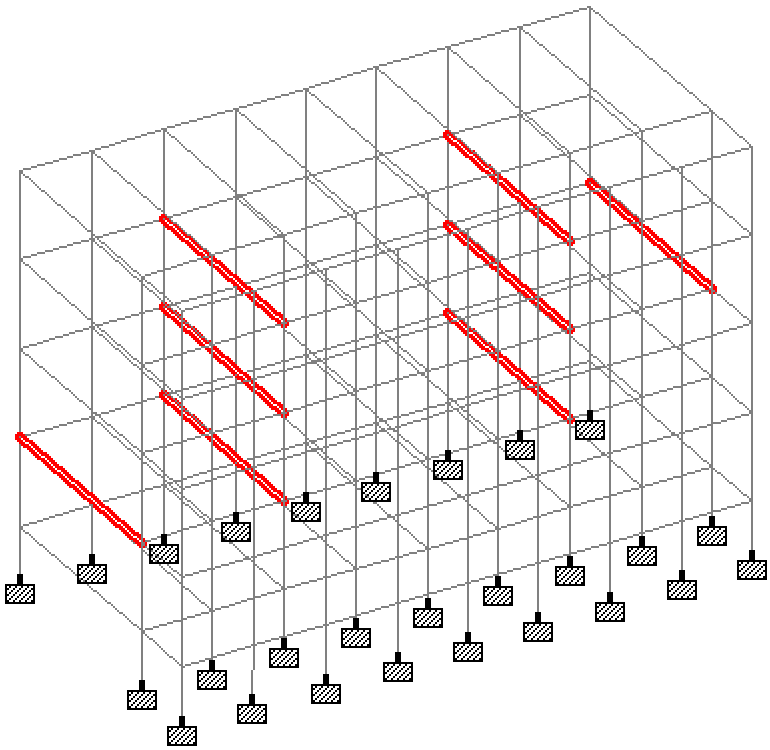


Fig. 4.2 Beams Failing due to Shear Capacity

4.1.2 DCR Calculations for Columns

Flexure Capacity of Columns

Table 4.3.1 1st Level

Column No.	Demand (kNm)	Capacity (kNm)	DCR	Result
352	26.384	25.515	1.034058397	FAIL
353	25.952	25.515	1.01712718	FAIL
354	32.554	25.515	1.275876935	FAIL
355	25.699	25.515	1.007211444	FAIL
356	34.657	25.515	1.35829904	FAIL
357	40.312	25.515	1.579933373	FAIL
358	32.443	25.515	1.271526553	FAIL

359	26.559	25.515	1.040917108	FAIL
360	24.558	25.515	0.962492651	PASS
363	82.374	18.88695	4.361424158	FAIL
364	140.198	18.88695	7.423009009	FAIL
365	216.939	22.308	9.72471759	FAIL
366	131.476	16.70625	7.869869061	FAIL
367	129.861	16.70625	7.773198653	FAIL
368	130.832	16.70625	7.831320614	FAIL
369	215.495	22.308	9.659987448	FAIL
370	130.419	16.70625	7.806599327	FAIL
371	163.128	14.3055	11.40316661	FAIL
374	209.662	9.443475	22.20178483	FAIL
375	135.942	9.443475	14.39533646	FAIL
376	212.667	44.616	4.766608392	FAIL
377	131.501	16.70625	7.871365507	FAIL
378	130.029	16.70625	7.78325477	FAIL
379	131.595	16.70625	7.876992144	FAIL
380	214.062	22.308	9.595750403	FAIL
381	130.962	16.70625	7.839102132	FAIL
382	158.025	9.537	16.569676	FAIL

Table 4.3.2 2nd Level

Column No.	Demand (kNm)	Capacity (kNm)	DCR	Result
44	17.553	25.515	0.687948266	PASS
45	24.14	25.515	0.946110131	PASS
46	23.632	25.515	0.926200274	PASS
47	23.673	25.515	0.927807172	PASS
48	23.506	25.515	0.921262003	PASS
49	23.311	25.515	0.91361944	PASS
50	23.487	25.515	0.920517343	PASS
51	24.767	25.515	0.970683911	PASS
52	22.542	25.515	0.883480306	PASS
55	209.589	18.88695	11.09702731	FAIL
56	174.32	18.88695	9.229653279	FAIL
57	237.502	44.616	5.323247266	FAIL
58	164.717	25.059375	6.573068961	FAIL
59	162.618	25.059375	6.489307894	FAIL
60	163.836	25.059375	6.537912458	FAIL
61	236.017	44.616	5.289963242	FAIL

62	163.813	25.059375	6.536994638	FAIL
63	192.295	33.3795	5.760871193	FAIL
66	211.581	28.330425	7.468331308	FAIL
67	170.387	18.88695	9.021414257	FAIL
68	234.417	133.848	1.751367223	FAIL
69	161.747	25.059375	6.454550443	FAIL
70	161.747	91.884375	1.760331939	FAIL
71	163.584	25.059375	6.527856341	FAIL
72	235.109	22.308	10.5392236	FAIL
73	163.841	16.70625	9.807167976	FAIL
74	184.273	14.3055	12.88126944	FAIL

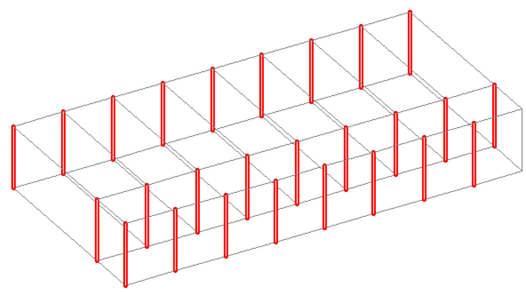
Table 4.3.3 3rd Level

Column No.	Demand (kNm)	Capacity (kNm)	DCR	Result
120	17.372	25.515	0.680854399	PASS
121	19.985	25.515	0.783264746	PASS
122	19.479	25.515	0.763433275	PASS
123	19.409	25.515	0.76068979	PASS
124	19.356	25.515	0.758612581	PASS
125	19.065	25.515	0.747207525	PASS
126	19.28	25.515	0.755633941	PASS
127	20.508	25.515	0.803762493	PASS
128	19.89	25.515	0.779541446	PASS
131	199.372	18.88695	10.55607179	FAIL
132	155.631	18.88695	8.240134061	FAIL
133	232.103	22.308	10.40447373	FAIL
134	145.077	16.70625	8.683995511	FAIL
135	142.488	16.70625	8.529023569	FAIL
136	144.236	16.70625	8.633655069	FAIL
137	230.434	22.308	10.32965752	FAIL
138	144.557	16.70625	8.652869435	FAIL
139	166.842	14.3055	11.66278704	FAIL
142	209.014	18.88695	11.06658301	FAIL
143	152.789	18.88695	8.089659792	FAIL
144	229.032	22.308	10.26681011	FAIL
145	144.749	16.70625	8.66436214	FAIL
146	142.298	16.70625	8.51765058	FAIL
147	144.717	16.70625	8.662446689	FAIL
148	229.645	33.462	6.862859363	FAIL

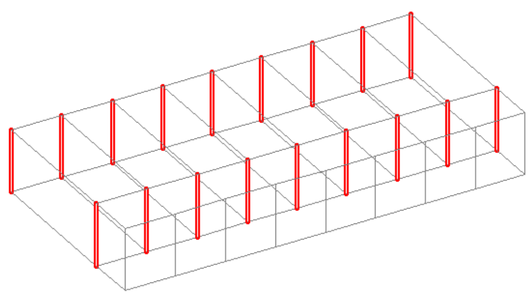
149	145.49	16.70625	8.708716798	FAIL
150	161.899	19.074	8.487941701	FAIL

Table 4.3.4 4th Level

Column No.	Demand (kNm)	Capacity (kNm)	DCR	Result
196	14.613	25.515	0.572721928	PASS
197	11.475	25.515	0.44973545	PASS
198	11.457	25.515	0.449029982	PASS
199	11.209	25.515	0.43931021	PASS
200	11.092	25.515	0.434724672	PASS
201	11	25.515	0.43111895	PASS
202	11.079	25.515	0.434215168	PASS
203	11.849	25.515	0.464393494	PASS
204	14.544	25.515	0.570017637	PASS
207	27.101	37.7739	0.717453056	PASS
208	179.803	18.88695	9.519959549	FAIL
209	204.281	44.616	4.578648915	FAIL
210	168.634	33.4125	5.047033296	FAIL
211	168.413	33.4125	5.040419005	FAIL
212	167.892	33.4125	5.024826038	FAIL
213	203.763	44.616	4.567038731	FAIL
214	168.67	33.4125	5.048110737	FAIL
215	150.159	19.074	7.872444165	FAIL
218	183.236	18.88695	9.701725265	FAIL
219	171.695	18.88695	9.090668424	FAIL
220	202.304	44.616	4.534337457	FAIL
221	167.703	33.4125	5.019169473	FAIL
222	168.206	33.4125	5.034223719	FAIL
223	167.641	33.4125	5.01731388	FAIL
224	202.658	44.616	4.542271831	FAIL
225	169.839	33.4125	5.083097643	FAIL
226	153.495	23.8425	6.437873545	FAIL



1st Level



2nd, 3rd and 4th Levels

Fig. 4.3 Columns Failing due to Flexural Capacity

Shear Capacity of Columns

Table 4.4.1 1st Level

Column No.	Maximum Shear (kN)	Shear Resisted (kN)	DCR	Result
352	11.698	86.99362737	0.13446962	PASS
353	13.686	86.99362737	0.157321868	PASS
354	13.449	86.99362737	0.154597531	PASS
355	13.519	86.99362737	0.155402188	PASS
356	13.526	86.99362737	0.155482653	PASS
357	13.424	86.99362737	0.154310154	PASS
358	13.442	86.99362737	0.154517065	PASS
359	13.883	86.99362737	0.159586402	PASS
360	11.963	86.99362737	0.13751582	PASS
363	101.726	167.5776989	0.607037814	PASS
364	72.06	156.6952589	0.459873518	PASS

365	114.086	214.2199579	0.532564758	PASS
366	66.45	148.4329474	0.447676888	PASS
367	65.493	148.4329474	0.441229533	PASS
368	66.084	148.4329474	0.445211128	PASS
369	113.523	214.2199579	0.529936618	PASS
370	66.634	148.4329474	0.448916505	PASS
371	73.348	109.4014737	0.670448007	PASS
374	106.604	144.0161396	0.740222591	PASS
375	70.365	144.0161396	0.488591072	PASS
376	112.273	193.904	0.579013326	PASS
377	66.003	137.3652745	0.480492615	PASS
378	65.109	137.3652745	0.47398442	PASS
379	66.162	137.3652745	0.481650113	PASS
380	112.936	193.904	0.582432544	PASS
381	67.114	137.3652745	0.48858054	PASS
382	69.354	95.95397368	0.722784032	PASS

Table 4.4.2 2nd Level

Column No.	Maximum Shear (kN)	Shear Resisted (kN)	DCR	Result
44	11.665	86.77550737	0.134427333	PASS
45	12.765	86.77550737	0.147103721	PASS
46	12.496	86.77550737	0.144003768	PASS
47	12.533	86.77550737	0.144430155	PASS
48	12.517	86.77550737	0.144245771	PASS
49	12.342	86.77550737	0.142229073	PASS
50	12.434	86.77550737	0.14328928	PASS
51	13.099	86.77550737	0.150952733	PASS
52	11.587	86.77550737	0.133528462	PASS
55	91.789	167.4796589	0.548060586	PASS
56	125.763	141.7931789	0.886946755	PASS
57	86.723	194.1944	0.446578274	PASS
58	85.635	136.9368245	0.625361369	PASS
59	86.265	136.9368245	0.62996203	PASS
60	125.009	136.9368245	0.912895421	PASS
61	86.781	191.6568	0.452793744	PASS
62	87.092	136.9368245	0.636001312	PASS
63	11.665	95.95397368	0.121568702	PASS
66	112.347	143.6729996	0.78196321	PASS
67	90.016	141.7931789	0.634840129	PASS

68	124.087	202.0759579	0.614061174	PASS
69	86.364	131.2949474	0.657786166	PASS
70	85.392	180.0931474	0.474154632	PASS
71	86.36	131.2949474	0.6577557	PASS
72	124.58	158.8566933	0.784228838	PASS
73	87.24	131.2949474	0.664458167	PASS
74	81.899	95.95397368	0.853523797	PASS

Table 4.4.3 3rd Level

Column No.	Maximum Shear (kN)	Shear Resisted (kN)	DCR	Result
120	10.101	86.77550737	0.116403814	PASS
121	10.456	86.77550737	0.12049483	PASS
122	10.165	86.77550737	0.117141349	PASS
123	10.137	86.77550737	0.116818677	PASS
124	10.049	86.77550737	0.115804566	PASS
125	9.958	86.77550737	0.114755883	PASS
126	10.064	86.77550737	0.115977426	PASS
127	10.735	86.77550737	0.123710023	PASS
128	10.217	86.77550737	0.117740597	PASS
131	91.978	174.8326589	0.526091638	PASS
132	78.005	123.7293089	0.630448846	PASS
133	115.54	194.8423579	0.592992208	PASS
134	73.53	117.8551474	0.623901473	PASS
135	72.367	117.8551474	0.614033427	PASS
136	73.118	117.8551474	0.620405656	PASS
137	114.766	188.4850824	0.608886383	PASS
138	73.807	111.7484745	0.66047434	PASS
139	77.096	95.95397368	0.803468549	PASS
142	94.796	167.6022089	0.565601137	PASS
143	76.432	123.7293089	0.617735609	PASS
144	73.267	188.4850824	0.388715113	PASS
145	72.167	117.8551474	0.612336428	PASS
146	73.222	117.8551474	0.621288095	PASS
147	114.534	117.8551474	0.971820091	PASS
148	74.511	188.4850824	0.395315104	PASS
149	73.609	117.8551474	0.624571787	PASS
150	91.978	95.95397368	0.958563741	PASS

Table 4.4.4 4th Level

Column No.	Maximum Shear (kN)	Shear Resisted (kN)	DCR	Result
196	6.53	86.77550737	0.075251649	PASS
197	5.863	86.77550737	0.067565148	PASS
198	5.794	86.77550737	0.066769993	PASS
199	5.676	86.77550737	0.065410162	PASS
200	5.616	86.77550737	0.064718723	PASS
201	5.571	86.77550737	0.064200143	PASS
202	5.599	86.77550737	0.064522815	PASS
203	6.055	86.77550737	0.069777754	PASS
204	7.136	86.77550737	0.082235186	PASS
207	87.133	190.8376889	0.456581719	PASS
208	85.247	183.6072389	0.464289973	PASS
209	103.741	194.1944	0.534212109	PASS
210	82	165.0174833	0.496917044	PASS
211	81.54	173.8016974	0.469155372	PASS
212	81.666	173.8016974	0.469880336	PASS
213	103.433	194.1944	0.53262607	PASS
214	80.891	173.8016974	0.465421231	PASS
215	61.911	132.5839737	0.46695689	PASS
218	85.159	183.5827289	0.463872612	PASS
219	83.654	183.5827289	0.455674673	PASS
220	102.973	194.1944	0.530257309	PASS
221	81.789	173.8016974	0.470588039	PASS
222	81.475	173.8016974	0.468781383	PASS
223	81.708	173.8016974	0.470121991	PASS
224	103.452	194.1944	0.53272391	PASS
225	81.755	173.8016974	0.470392414	PASS
226	61.825	134.6794737	0.459052878	PASS

4.1.3 FRP Design Calculations

Table 4.5.1 Beams on 1stStorey

Beam No.	Demand Moment (kNm)	ΦM_n(kNm)	$f_{s,s}$(N/mm^2)	$f_{f,s}$(N/mm2)	No. of plies
1	44.484	73.606	42.843	8.704	2
2	42.166	73.603	46.409	9.429	2
3	42.105	73.603	45.787	9.302	2
4	41.664	73.603	44.652	9.072	2
5	41.785	73.604	44.652	9.072	2
6	42.158	73.603	45.841	9.313	2
7	41.522	73.605	44.381	9.016	2
8	44.431	73.607	40.465	8.221	2
11	44.328	44.581	65.29	13.465	3
13	101.59	105.26	61.986	12.615	6
14	102.405	105.248	66.404	13.514	6
15	99.518	105.254	64.868	13.201	6
16	92.931	105.28	58.09	11.822	6
17	92.767	105.281	57.412	11.684	6
18	98.034	105.259	64.401	13.106	6
19	100.019	105.255	64.472	13.121	6
20	92.615	105.28	55.364	11.267	6
23	400.526	402.935	196.815	38.647	11
24	109.261	116.137	49.397	9.973	5
25	112.292	116.12	52.977	10.696	5
26	106.209	116.134	49.01	9.895	5
27	97.311	116.155	42.166	8.513	5
28	97.158	116.158	41.036	8.285	5
29	105.714	116.132	50.264	10.148	5
30	107.219	116.134	48.792	9.851	5
31	97.257	116.154	41.951	8.47	5
35	306.418	400.504	71.041	13.987	2
37	294.079	325.429	87.786	17.267	2
38	291.341	315.971	89.603	17.622	2
39	292.528	315.971	89.885	17.678	2
41	294.893	315.972	89.787	17.658	2
42	220.503	232.143	91.712	18.007	5
386	42.932	48.863	41.931	8.651	4

Table 4.5.2 Beams on 2ndStorey

Beam No.	Demand Moment (kNm)	ΦM_n(kNm)	$f_{s,s}$(N/mm^2)	$f_{f,s}$(N/mm2)	No. of plies
77	41.635	73.609	39.005	7.924	2
78	39.868	73.603	46.707	9.489	2
79	39.349	73.603	45.814	9.308	2
80	38.981	73.604	44.76	9.093	2
81	38.954	73.604	44.544	9.05	2
82	39.358	73.603	45.814	9.308	2
83	39.193	73.604	45.247	9.192	2
84	41.485	73.61	36.816	7.749	2
87	39.57	44.369	49.94	10.299	3
89	94.49	96.42	67.259	13.691	5
90	97.854	96.408	72.289	14.715	5
91	94.792	96.415	69.906	14.23	5
92	87.456	96.443	61	12.446	5
93	87.048	96.446	60.114	12.237	5
94	93.008	96.419	69.87	14.223	5
95	95.088	96.417	69.193	14.085	5
96	86.691	96.449	57.286	11.661	5
100	99.675	109.065	57.019	10.904	4
101	106.372	109.044	58.771	11.863	4
102	100.11	109.05	53.721	10.844	4
103	90.447	109.083	44.247	8.931	4
104	90.01	109.083	43.37	8.754	4
105	99.33	109.056	55.529	11.209	4
106	100.827	109.06	53.033	10.705	4
107	89.468	109.084	43.663	8.814	4
112	440.714	526.493	86.417	17.0426	3
113	290.215	332.21	88.504	17.409	3
114	287.427	323.03	90.007	17.703	3
115	288.638	323.03	90.337	17.768	3
116	438.591	532.37	85.52	16.67	5
117	289.386	340.02	87.113	17.136	5
118	354.727	357.75	65.862	12.945	18
385	44.394	48.858	36.669	8.185	4

Table 4.5.3 Beams on 3rd Storey

Beam No.	Demand Moment (kNm)	ΦM_n(kNm)	$f_{s,s}$(N/mm^2)	$f_{f,s}$(N/mm2)	No. of plies
163	32.127	38.734	53.916	11.133	2
165	74.554	85.805	75.008	15.261	3
166	80.358	85.791	80.966	16.473	3
167	77.532	85.798	77.633	15.795	3
168	70.557	85.817	67.511	13.736	3
169	69.716	85.82	65.793	13.386	3
170	75.755	85.8	78.099	15.89	3
171	77.483	85.879	76.936	15.653	3
176	76.084	93.185	60.706	12.249	2
177	85.568	93.173	66.24	13.402	2
178	80.124	93.18	60.409	12.189	2
179	71.249	93.193	48.624	9.811	2
180	70.217	93.193	48.33	9.752	2
181	79.147	93.179	62.575	12.626	2
182	80.246	93.181	59.649	12.036	2
183	68.936	93.196	47.963	9.678	2
188	429.371	526.496	85.604	16.882	3
189	264.009	338.326	87.495	17.212	4
190	262.013	333.301	89.032	17.513	4
191	262.65	333.3	89.345	17.574	4
192	428.915	529.454	84.706	16.706	4
193	265.966	329.984	89.272	17.56	4
194	190.509	219.669	96.77	18.998	4

Table 4.5.4 Beams on Terrace

Beam No.	Demand Moment (kNm)	ΦM_n(kNm)	$f_{s,s}$(N/mm^2)	$f_{f,s}$(N/mm2)	No. of plies
239	26.452	38.714	62.536	12.889	2
241	32.311	66.762	48.442	9.84	2
242	37.358	66.754	52.987	10.764	2
243	34.641	66.758	48.28	9.807	2
244	29.257	66.796	37.341	7.585	2
245	29.388	66.769	36.705	7.456	2
246	33.476	66.759	49.095	9.973	2

247	35.213	66.76	47.389	9.627	2
248	28.521	66.771	36.116	7.336	2
251	181.786	204.957	104.54	20.52	2
253	42.967	93.204	37.269	7.52	2
263	177.643	211.898	105.95	20.804	2
264	182.458	232.06	96.208	18.897	2
265	170.208	203.564	107.47	21.099	2
266	168.496	203.565	106.391	20.887	2
267	170.079	203.564	107.299	21.066	2
268	180.97	232.061	95.488	18.756	2
269	169.737	204.663	106.93	20.993	2
270	160.556	179.442	110.473	21.679	2
383	31.084	43.301	71.507	14.757	2

4.2 Conclusions

The analysis of beams by Equivalent Static Method revealed that most of the beams failed in flexural capacity. The number of failing beams decreased with increasing storeys. However, the number of beams failing in shear capacity were very less i.e. beams 23, 36, 40 in 1st storey; 112, 116, 118 in 2nd storey; 188, 192 in 3rd storey.

For columns too, the analysis revealed that most of them failed in flexural capacity but were safe in shear.

Based on the above observations, the immediate need to counter deficiency in flexural capacity was identified and the FRP jacketing scheme was suggested only for beams, failing in flexure. Due to the high tensile strength and stiffness, stability under high temperatures and resistance to acidic/alkali/organic environments, carbon fiber was chosen as the FRP material to be used.

FRP strips that are commercially available are not made to a universal standard but a localized standard as set by the manufacturing company. Thus, the dimensions considered for the strips were strictly as per a design example in ACI 440.2R-02. The code states though, that wider and thinner FRP strips have lower bond stresses and hence, provide higher level of strength. Also, the plies were assumed to be bonded to the soffit of the beam using wet layup technique. A more confining wrapping scheme would have increased the strength further and hence, decreased the amount of FRP required.

The FRP design method used in this project is essentially trial and error where the value of the depth of neutral axis has to be assumed and compared with the value obtained. Thus, efforts were made so that the number of plies to be applied to a continuous series of beams, say in the longitudinal or transverse direction, would remain the same. This would ensure feasibility of application of the FRP system to the beams.

4.3 Scope of Future Work

FRP is a relatively new genre of materials used in the realm of civil engineering and a lot of its properties are yet to be determined. Future work needs to be done to determine its behavior in specific conditions.

Due to lack of design procedures in ACI 440.2R-02, the design was implemented only for beams. The project can be extended by suggestions on how to strengthen columns. Also, schemes for shear strengthening of the failing members should be developed.

Lastly, the same 4-storey RC structure can be retrofitted using some different technique like base isolation, steel bracings, shear wall etc. and a comparative study can be done to find out the most efficient technique with respect to cost, aesthetics, durability and other such criteria.

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